Asteroseismology of Solar-type Stars with Kepler I: Data Analysis

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We report on the first asteroseismic analysis of solar-type stars observed by Kepler. Observations of three G-type stars, made at one-minute cadence during the first 33.5d of science operations, reveal high signal-to-noise solar-like oscillation spectra in all three stars: About 20 modes of oscillation can clearly be distinguished in each star. We discuss the appearance of the oscillation spectra, including the presence of a possible signature of faculae, and the presence of mixed modes in one of the three stars.

1 Introduction

The year 2009 marked an important milestone in asteroseismology, with the launch of the NASA *Kepler* Mission (Gilliland et al. 2010). *Kepler* will realize significant advances in our understanding of stars, thanks to its asteroseismology program, particularly for cool (solar-type) main-sequence and subgiant stars that show solar-like oscillations, i.e., small-amplitude oscillations intrinsically damped and stochastically excited by the near-surface convection (see Christensen-Dalsgaard 2004 for a recent review). Solar-like oscillation spectra have many modes excited to observable amplitudes. The rich information con-

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tent of these seismic signatures means that the fundamental stellar properties (e.g., mass, radius, and age) may be measured and the internal structures constrained to levels that would not otherwise be possible (e.g., see Gough 1987; Cunha et al. 2007).

For its first ten months of science operations, *Kepler* will survey around 2000 solar-type stars for solar-like oscillations, with each star being observed for one month at a time. After this initial "Survey Phase" approximately 100 solar-type stars will be selected for long-term observations. At the time of writing, the number of known solar-type oscillators has increased by approximately one order of magnitude, thanks to *Kepler*. This is with only about 40 % of the total Survey Phase data available. The large homogenous sample of data presented by Kepler opens the possibility to conduct a seismic survey of the solar-type part of the colour-magnitude diagram, to compare trends in observed properties with trends predicted from stellar structure and evolutionary models.

In the *Kepler Asteroseismic Science Consortium* (KASC) Working Group #1 has responsibility for asteroseismic analysis of solar-type stars. First results were presented by Chaplin et al. (2010) on three G-type stars, and many publications from the Survey Phase are planned for the second half of 2010.

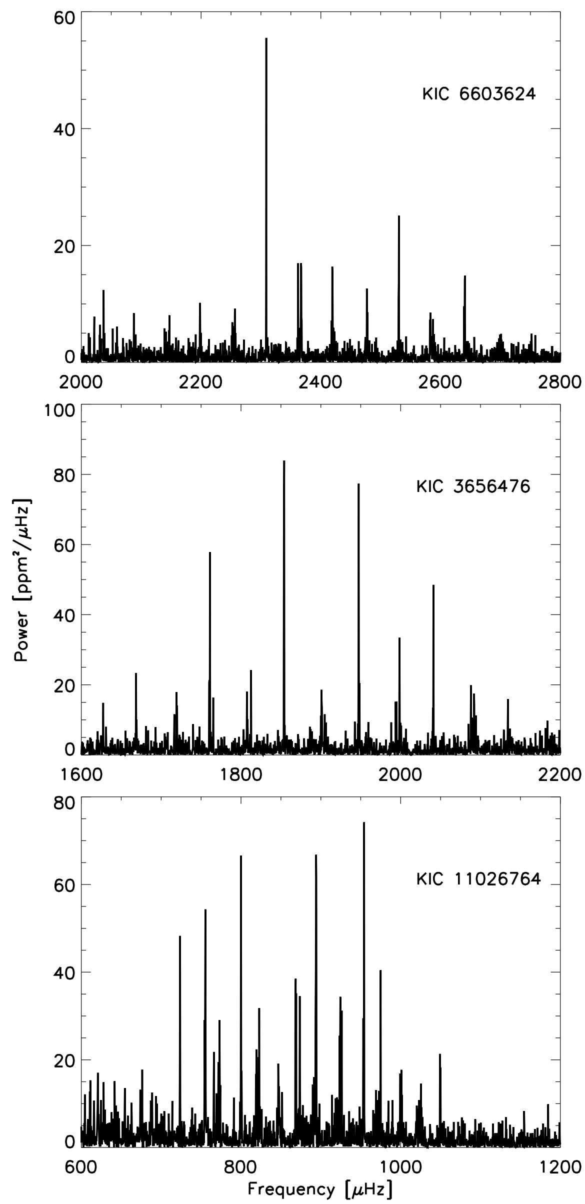

Fig. 1 Power density spectra of the three G-type stars analyzed by Chaplin et al. (2010)

2 Kepler Asteroseismic Science Consortium Working Group #1: Solar-Like Oscillators

The KASC Working Group #1 is responsible for the data analysis and modeling of the solar-type stars observed by *Kepler*. The Group, which is chaired by W. J. Chaplin, is divided into nine sub-groups:

1 – Extraction of Mean Parameters
chair: R. A. García
2 – Extraction of individual mode parameters
chair: T. Appourchaux
3 – Analysis of Mode Excitation and Damping
chair: G. Houdek
4 – The Stellar Background
chair: C. Karoff
5 – Model Grid Comparison
chair: T. S. Metcalfe
6 – Fitting Models to Observed Frequencies
chair: M. J. P. F. G. Monteiro
7 – Modeling Rotation, Mixing and New Physics
chair: M. J. Thompson
8 – Analysis of Long-Term Variations
chair: Y. Elsworth
9 – Ground-based Follow-Up
chair: J. Molenda-Żakowicz

This paper gives a brief summary of the work undertaken by sub-groups 1 to 4 on the three G-type dwarfs in Chaplin et al. (2010). Metcalfe et al. (this volume) and Molenda-Żakowicz et al. (this volume) describe, respectively, the corresponding work performed by sub-groups 5 to 7, and sub-group 9.

Recent improvements in the quality of asteroseismic observations, in particular from the excellent quality CoRoT data (Michel et al. 2008), but also from other space- and ground-based observing facilities, have driven improvements in asteroseismic data analysis techniques. These improvements have been followed by significant work on preparing for the mode-parameter analysis of the Kepler data. This analysis involves the estimation of individual and average mode parameters, and also estimation of parameters that describe non-resonant signatures of convection and activity that are present in the *Kepler* data. Examples include

work conducted in the framework of asteroFLAG (Chaplin et al. 2008); and work undertaken by the CoRoT Data Analysis Team (e.g., Appourchaux et al. 2008). This has led to the development of suites of analysis tools for application to the *Kepler* data (e.g., see Campante et al. 2010; Hekker et al. 2010; Huber et al. 2009; Karoff et al. 2010; Mathur et al. 2010; Mosser & Appourchaux 2009, Roxburgh 2009). The levels of preparedness meant that analysis of the first observations of solar-type stars by *Kepler* (see Fig. 1) could be made in a timely fashion, in order to meet the publication deadlines set down by NASA. Shown below is a list of the different tasks that were conducted for the Chaplin et al. (2010) paper:

21 Oct – Data received
23 Oct – Global seismic analysis
26 Oct – Paper written and sent to sub-group chairs
2 Nov – Paper approved by working sub-group chairs and sent to working group members
16 Nov – Paper approved by working group members and submitted

3 Signatures of convection in the stellar background

Power-frequency spectra of photometric observations of the Sun and other solar-type stars show not only signatures of oscillations, but also signatures arising from other intrinsic stellar phenomena. In order of increasing frequency there is power due to: rotational modulation of effects of magnetic activity, like starspots, and also the decay of active regions; granulation; and faculae. We might also hope in the future to be able to detect signatures of chromospheric oscillations and high-frequency waves, both of which are observed in the Sun.

The characteristic timescales and amplitudes of the components arising from the decay of active regions, granulation, and faculae are commonly represented using a Harvey-like model (Harvey 1985):

$$B(\nu) = \sum_i \frac{4\sigma_i^2\tau_i}{1+(2\pi\nu\tau_i)^\alpha} + c, \tag{1}$$

where σ is the amplitude of the component, τ is the characteristic timescale, ν is the frequency and c is a constant that give the white noise level. The exponent α depends on the "memory" of the physical process responsible for the component.

Chaplin et al. (2010) were able to measure not only the characteristic timescales and amplitudes of the granulation component, but also the presence (and properties of) a component assumed to be the signature of faculae (marked by the arrow in Fig. 2). We are now in the process of measuring the characteristic timescales and amplitudes of the different background components in around 200 solar-type stars observed during the first four months of the Kepler asteroseismic survey. These stars have been selected because they show clear the signatures of solar-like oscillations, meaning that we will also be able to perform a full asteroseismic analysis of their data to provide estimates of masses, radii and ages. The aim of this study will be to identify how signatures of convection and activity vary with stellar properties.

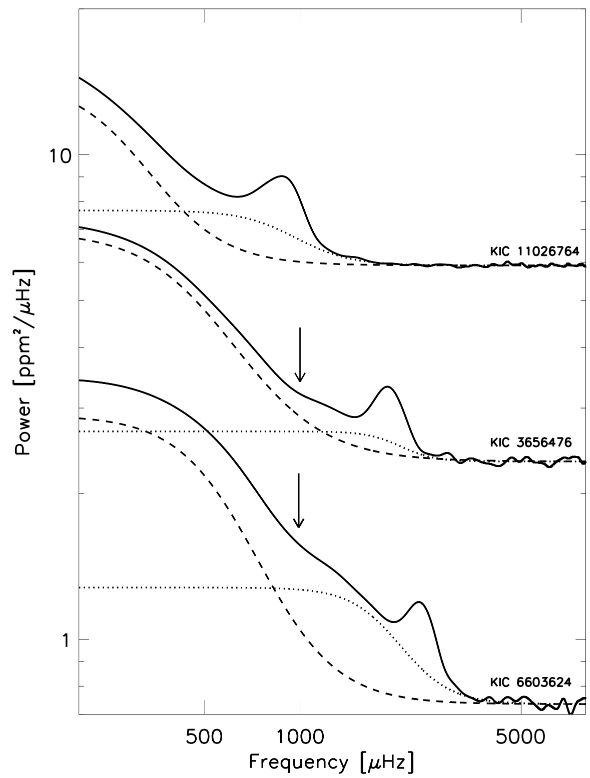

Fig. 2 Power density spectra of the three G-type stars analyzed by Chaplin et al. (2010), smoothed by Gaussian running-means of width of two times the large frequency separations. The spectra of KIC 3656476 and KIC 11026764 have been shifted upwards by 1 and 5 ppm^2/μHz, respectively. The arrows mark the locations of the signature of faculae. The dashed and dotted lines show the best-fitting models of the granulation and facular components, respectively.

4 The Echelle diagrams

Solar-like p modes of high radial order and low angular degree are reasonably well-described by the asymptotic relation (Tassoul 1980):

$$\nu_{n,l} \sim \Delta\nu(n + l/2 + \epsilon) - l(l+1)D_0. \tag{2}$$

Here, n (the radial order) and l (the angular degree) are integers. D_0 is the small frequency separation parameter and ϵ is a phase constant determined by the reflection properties near the surface.

Departures of stellar oscillation frequencies from the asymptotic relation may be shown visually by plotting the oscillation power in a so-called échelle diagram (Grec et al. 1983), as is done in Fig. 3. Here, the oscillation power

for each star has been plotted against the frequencies modulo the average large frequency separation. Individual strips of the power spectrum are offset vertically, such that the mean value of each échelle order gives the lower frequency of each échelle order.

Were a star to obey strictly the asymptotic relation, its frequencies would lie in vertical ridges in the échelle diagram. The échelle diagrams in Fig. 3 show that stars KIC 6603624 and KIC 3656476 exhibit only small departures from an asymptotic description, whereas KIC 11026764 shows clear deviations in its l = 1 ridge. These deviations are due to the fact that this star has started to evolve off the main sequence and thus shows avoided crossings (Osaki 1975; Aizenman et al. 1977). Avoided crossings result from interactions between acoustic modes and buoyancy modes, which affect (or "bump") the frequencies and also change the intrinsic properties of the modes, with some taking on mixed acoustic and buoyancy characteristics. The precise signatures of these avoided crossings are very sensitive to the evolutionary state of the star. It is therefore reasonable to assume that the presence of mixed modes will improve significantly the age determination of stars,

For solar-type stars $\Delta\nu$ provides a measure of the inverse of the sound travel time across the star, while D_0 is sensitive to the sound-speed gradient near the core. It is conventional to define two small frequency separations: $\delta\nu_{02}$, which is the spacing between adjacent modes of l = 0 and l = 2; and $\delta\nu_{13}$, the spacing between adjacent modes of l = 1 and l = 3. The asymptotic relation then predicts that $\delta\nu_{02} = 6D_0$ and $\delta\nu_{13} = 10D_0$. The spacings $\delta\nu_{02}$ are seen clearly in all three stars. It is normally assumed that l = 3 modes are too weak to be visible in stellar photometric observations like the ones we have from *Kepler* (Kjeldsen et al. 2008). None of the three stars reported here shows convincing evidence for l = 3 modes; however, preliminary analyses of *Kepler* Survey data do show possible evidence of l = 3 modes in some stars.

We add in passing that KIC 3656476 does show signs of extra power on the high-frequency side of its l = 1 mode at $\approx$ 1770 μHz (marked by the arrow in Fig. 3). We do not expect this power to be due to the presence of an l = 3 mode. Such power would lie on the low-frequency side of the stronger l = 1 mode, like its l = 2 counterparts, which for this star clearly lie on the low-frequency side of their l = 0 neighbours. Aside from the possibility this might be an artifact, it is conceivable that the extra power might be the signature of a mixed mode (see also Bedding et al. 2010 for a discussion of this).

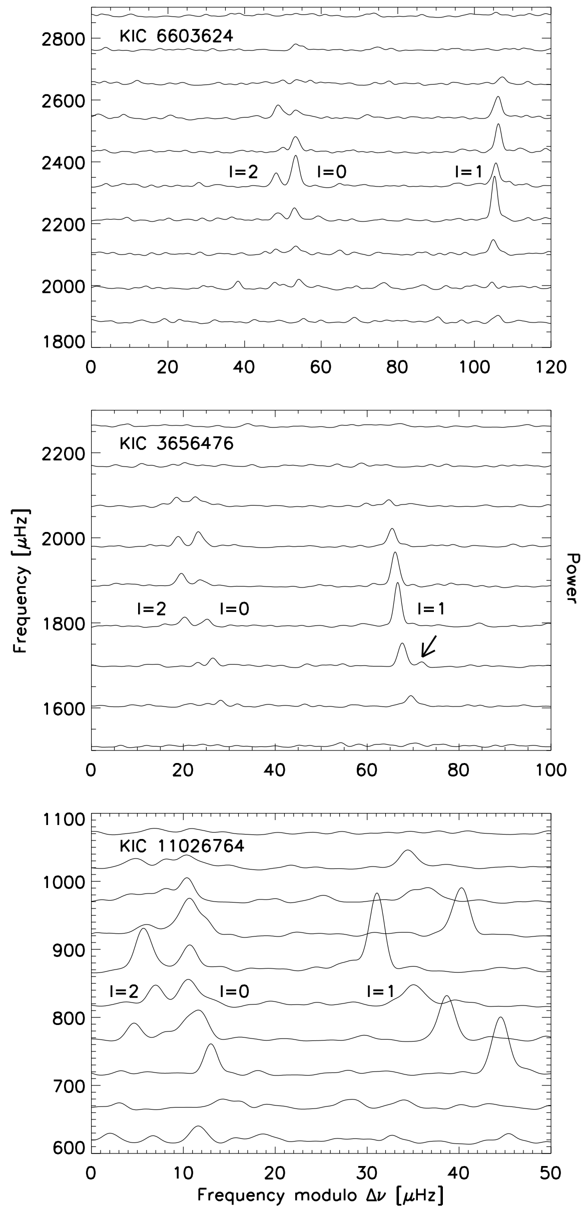

Fig. 3 Echelle diagrams of the three G-type stars analyzed by Chaplin et al. (2010). The spectra have been smoothed by a Gaussian running-mean with a width of 2 μHz, before substrings of the spectra were stacked on top of one another. The large separation in the three stars were measured to 110.2 ± 0.6, 94.1 ± 0.6 and 50.8 ± 0.3 μHz (from top to bottom).

5 Individual mode parameters

At the time of writing we have access to data on a few hundred solar-type stars. The quality of these data is such that it is possible to extract estimates of individual frequencies, amplitudes, and also some mode lifetimes, in a large fraction of the targets showing evidence for solar-type oscillations. It may also be possible to extract estimates of rotational splittings in some of the more rapidly rotating stars.

The analysis of the three G-type stars has shown that not only can the oscillation mode frequencies and amplitudes be measured with high precision, but it is also possible to place constraints on the mode lifetimes, which in all three cases appear to be similar in length to the Sun. Moreover, the anal-

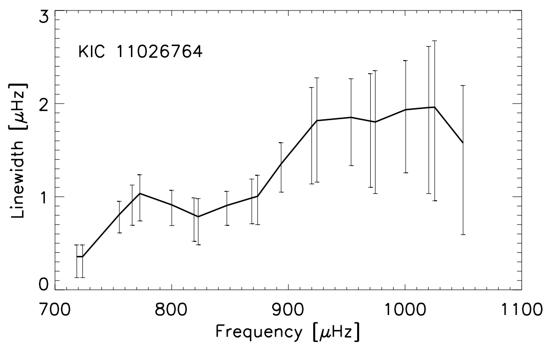

Fig. 4 Oscillation mode linewidth for KIC 11026764. Note how similar the change in linewidth as a function of frequency is to what has been observed for the Sun.

ysis of KIC 11026764 show that the mode lifetimes plateau is at frequencies close to the frequency of maximum power $\nu_{\max}$ (see Fig. 4), just as for the Sun (see Chaplin et al. 2009 for a discussion of the predictions of mode lifetimes).

The observed maximum mode amplitudes of the three stars are all higher than solar. This is in line with predictions from simple scaling relations (Kjeldsen & Bedding 1995; Samadi et al. 2007), which use the inferred fundamental stellar properties as input. Data from a larger selection of survey stars are required before we can say anything more definitive about the relations.

Kepler will deliver multi-year datasets for the best solar-type asteroseismic targets, and from these data we expect to be able to extract: signatures of rapid structural changes in the stellar interiors, from the borders of convective regions and from zones of ionization in the near-surface layers; rotational splittings as a function of n and l, and possibly subtle signatures originating from differential rotation; and changing oscillation mode frequencies and amplitudes due to stellar cycles (see Karoff et al. 2009 for details)

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